Brillouin Selective Sideband Amplification of Microwave Photonic Signals

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Abstract— **We introduce a powerful Brillouin selective sideband amplification technique and demonstrate an important application for achieving gain in photonic signal up- and down-conversions in microwave photonic systems. We show that systems employing such a scheme is also automatically immune to the fiber dispersion effect.**

Index Terms— **Brillouin scattering, down-conversion, microwave photonics, microwave, optical amplification, sidebands, signal mixing, up-conversion.**

I. Introduction

Brillouin amplification in digital photonic systems has been extensively studied by many authors. Unfortunately, it has been proved to be impractical due to its narrow bandwidth and high spontaneous emission noise [1], [2]. In this letter, we introduce a powerful selective sideband amplification scheme and demonstrate an important application for analog communication systems that fully exploits the advantages of Brillouin amplification and circumvents its disadvantages.

In Brillouin amplification [3], an optical pump with a frequency of ν_p entering a length of optical fiber generates an acoustic grating moving in the direction of the pump, which gives rise to backscattering of the optical pump. The frequency of the backscattered light is down shifted, via the Doppler effect, from the pump by $\nu_B = 2\nu_p(\nu_a/\nu_l)$, where ν_a and ν_l are the speed of the acoustic wave and the speed of light in the fiber, respectively. If a narrow-band seed signal with a frequency of $\nu_p - \nu_b$ is injected into the fiber from the opposite end of the pump, the interaction of the seed signal with the pump will greatly enhance the induced acoustic grating, causing more backscattering of the pump into the seed and effectively amplifying the seed signal.

II. The Concept of Selective Sideband Amplification

The concept of brillouin selective sideband amplification (BSSA) introduced in this work is illustrated in Fig. 1(a) and (b). Unlike the selective carrier amplification [4], [5], here the narrow bandwidth of Brillouin amplification is used to advantage to selectively amplify one of the weak sidebands (which carries information) and leave the strong carrier (which carries no information) unchanged. The RF (frequencies ranging from radio up to millimeter wave) signal in the photodetector will be the beat between the strong carrier and the amplified sideband.

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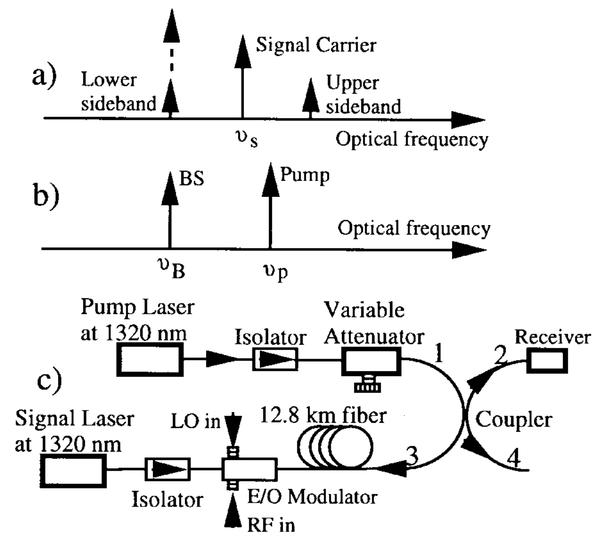

Fig. 1. (a) The typical spectrum of an RF signal imposed on an optical carrier. (b) The spectrum diagram showing the frequencies of the pump and the Brillouin scattering. When the frequency of one of the sidebands coincides with the frequency of the Brillouin scattering, it will be amplified. (c) The experimental setup for demonstrating Brillouin selective sideband amplification.

In this way we can dramatically increase the modulation index of the received RF signal and amplify it. In practice, one can either tune the frequency of the pump laser or the frequency of the signal laser so that one of the modulation sidebands coincides with the frequency of the Brillouin scattering and gets amplified. Compared with other optical amplidiers, such as an Er^{+3}-doped fiber amplifier (EDFA), this scheme is much more efficient because all Brillouin scattering energy from the pump laser goes into the information-carrying weak sideband. Furthermore, because the strong carrier is not amplified, the saturation of the receiving photodetector can be avoided.

Fig. 1(c) is the experimental setup for demonstrating Brillouin selective sideband signal amplification of RF signals. In the experiment, a $LiNbO_3$ Mach–Zehnder modulator was used to modulate the optical carrier emitted by a signal laser (diode pumped YAG laser) at 1320 nm. The resulting optical signal is finally injected into the 12.8-km fiber from the opposite of the pump laser (also a diode pumped YAG laser). Isolators were used in front of the pump and signal lasers to prevent light from one laser entering the other.

Experimental results demonstrating the BSSA technique are shown in Fig. 2(a) and (b). In the figure, the broad peak (~10 MHz) is the beat between the signal carrier and the Brillouin scattering, and its width represents the Brillouin gain bandwidth. The clean narrow peak is the received RF signal or the beat of the signal carrier and the RF modulation sidebands.

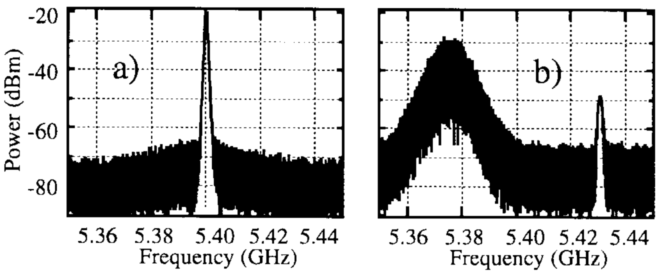

Fig. 2. Experimental results demonstrating Brillouin selective sideband amplification. (a) Pump is tuned to be aligned with a signal sideband. An RF gain of 31.5 dB is observed. (b) The pump laser is tuned two gain bandwidths away and the RF gain decreased to 3 dB. The frequency span of the measurement is 100 MHz and the noise bandwidth is 1 MHz. The input RF signal is at 5.43 GHz with a power of −2.17 dBm.

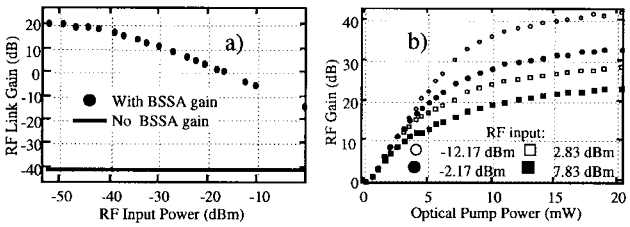

Fig. 3. (a) RF link gain as a function of RF input power to the modulator. A small-signal link gain of 20 dB was obtained with only 2.61-mW optical power in the photodetector. The gain decreases at high-input RF power levels. The optical pump power in the experiment is 12.23 mW. (b) The gain of RF signals versus optical pump power for different RF input powers to the modulator. Substantial RF gain was obtained even when the pump power is much lower than the SBS threshold level of 10 mW. Note that the gain saturates at high-optical pump powers.

It is evident that when the lower sideband of the RF signal is aligned with the Brillouin scattering peak, it is amplified with a gain of more than 30 dB. When the Brillouin scattering peak is tuned away from the sideband, the amplification diminishes gradually.

The RF link gain (defined as the difference of the RF output power from the photodetector and the RF input power to the modulator in dB) as a function of RF input power is shown in Fig. 3(a). With a pump power of only 12.23 mW, a small-signal RF link gain of more than 20 dB at 5.5 GHz is achieved. As a comparison, the RF link loss without Brillouin selective sideband amplification is about −41 dB. This accounts for a total RF signal amplification of 61 dB.

Finally, Fig. 3(b) shows the RF signal gain versus optical pump power for different input RF power. It is evident that a substantial gain of the RF signals can be achieved even when the optical power is much less than the SBS threshold. At high pump powers, the gain also saturates. Part of the observed gain saturation may be due to the photodetector saturation.

III. Properties of BSSA

We found that the BSSA has the following properties. First, it is very efficient and requires very low pump power. A DFB laser with a few milliwatts output power is sufficient to achieve adequate signal amplification. Consequently, it is much less expensive to implement than an EDFA or an SOA. Second, it has very narrow gain bandwidth that is advantageous for the efficient selective sideband amplification; however it is not useful for directly amplifying signals with wide bandwidths. Third, the gain of the weaker signal is generally higher, however this is accompanied by higher amplifier noise caused by the spontaneous emission. If the seed signal is sufficiently strong, the stimulated emission induced by the seed will dominant and deplete the energy that may otherwise be converted to noise (spontaneous emission). For an externally modulated link, we found experimentally that the amplifier noise is insignificant if the input RF signal is sufficiently strong to limit the RF gain to less than 30 dB. Finally, the gain saturates for large signals with a fast response time, which will cause intermodulation distortion. Despite the disadvantages, there are many applications in which the advantages of the Brillouin amplification can be fully utilized, while its limitations can be circumvented, such as in the example demonstrated below.

IV. Photonic RF Signal Mixing with Gain

Photonic signal mixing [6] is very important in microwave systems and has been demonstrated by many authors using two cascaded Mach–Zehnder modulators. One of the modulators is driven by the local oscillator (LO) and the other modulator is driven by the RF signal. The beating between the optical carrier and the RF modulation sidebands in the photodetector converts the signal back to electrical domain, while the beating between the LO modulation sidebands and the RF modulation sidebands in the photodetector produces the down and up converted signals. Because the LO sidebands are always much weaker than the optical carrier, the conversion process is always accompanied with a high loss.

As illustrated in Fig. 4(a) and (b), using Brillouin amplification one can dramatically increase one of the LO modulation sidebands when it is aligned with the Brillouin frequency. In the illustration, the lower LO modulation sideband is amplified. Since the down converted signal involves the beat between the lower LO sideband and the lower RF sideband, amplifying the lower LO sideband will increase the down-converted signal. Similarly, since the up-converted signal involves the beat between the lower LO sideband and the upper RF sideband, the amplification of the lower LO sideband will cause the up converted signal to be amplified. If the LO sideband is amplified to be larger than the carrier, the conversion will then experience a net gain.

It is important to notice that this BSSA assisted signal mixing is independent of the bandwidth of the RF signal in spite of the narrow bandwidth of the Brillouin amplification, because only the single tone LO sideband band is being amplified. Therefore, using Brillouin amplification for signal mixing can avoid the shortfall of its narrow amplification bandwidth. Although it is possible to amplify the RF signal sideband instead of LO to achieve the same intermediate frequency (IF) amplification, the signal bandwidth will be limited by the Brillouin amplification bandwidth. It should also be noticed that because only one of the LO sidebands (a single tone) is amplified, the intermodulation distortion from the gain saturation can be avoided. Finally, unlike in a digital fiber optic system in which the optical signal power is generally too weak for the stimulated emission process to dominate, the strong optical power in the LO sideband of the RF photonic system will effectively saturate the Brillouin gain and suppress

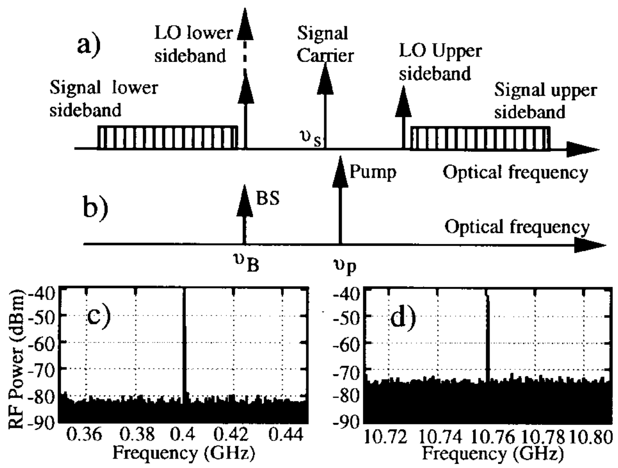

Fig. 4. (a) and (b) Spectrum diagrams illustrating the concept of photonic mixing with gain obtained by amplifying one of the LO sidebands. (c) Measured spectrum of down converted signal. (d) Measured spectrum of up converted signal. The LO and RF frequencies are 5.18 and 5.5873 GHz, respectively.

the spontaneous emission noise. In short, all the shortcomings of the Brillouin amplification (narrow gain bandwidth, nonlinearity from gain saturation, and high spontaneous emission noise) can be avoided with the approach above.

We performed two experiments to demonstrate photonic mixing with Brillouin gain. The setup for the first experiment is similar to Fig. 1(c). The modulator used in the experiment has two independent RF input ports with a mutual isolation of over 40 dB. An LO signal at a level of 4.83 dBm at 5.18 GHz was injected into one of the port and an RF signal of −5 dBm at 5.5873 GHz was injected into the other port. The modulator was biased at 50% of the transmission peak. Without the Brillouin amplification, the total optical power at the detector is 0.314 mW, the received LO is −40 dBm, and the received RF is −52 dBm. At an optical pump power of 12.112 mW, the Brillouin amplification increased the total optical power at the detector to 2.61 mW and increased the LO power to −15 dBm. The received down converted signal is −40 dBm and the up converted signal is −42 dBm, resulted in a down-conversion gain of 12 dB and up-conversion gain of 10 dB. The spectra of down converted signal and up converted signal are shown in Fig. 4(c) and (d). Similar results were also obtained in the second experiments with two cascaded Mach–Zehnder modulators.

V. Automatic Elimination of Fiber Dispersion Effect

A serious problem with present microwave photonic systems is the signal fading caused by fiber dispersion. When a modulated optical signal travels in a dispersive fiber, the lower sideband and the upper sideband have different speeds and, therefore, accumulate different phases. Because the final received signal after the photodetector is the sum of the beats of the optical carrier with the lower sideband and upper sideband respectively, the power of received signal is a periodic function of fiber distance. At the distances corresponding to 180° accumulated phase difference between the lower and upper sidebands, the received signal power is reduced to zero due to the destructive interference.

One may solve this problem by filtering out one of the sidebands [7] or using a single sideband modulator [8] to prevent the destructive interference between the lower and upper sidebands. Equivalent to the two approaches above, this signal fading problem can be eliminated if one of the sidebands is greatly amplified. Therefore, Brillouin selective sideband amplification not only amplifies the received microwave signals, but also automatically removes the signal fading problem caused by fiber dispersion. Such a signal fading elimination also extends to the photonic signal down- and up-conversion systems described above, where one of the LO sidebands is selectively amplified by BSSA.

VI. Summary

We have demonstrated the powerful scheme of BSSA. Such an amplification scheme is much more efficient than any other optical amplification schemes because the energy from the pump laser only goes into the information-carrying weak sideband. Furthermore, because the strong carrier is not amplified, the saturation of the receiving photodetector can be avoided. We also demonstrated broad-band photonic signal up- and down-conversions with 12-dB gain by using this scheme. This demonstration makes photonic mixing readily applicable without having to employ high-power lasers and high-power photodetectors. An added advantage of the scheme is that it automatically eliminates signal fading caused by fiber dispersion. We note that BSSA can also provide many other important functionalities [9] for the photonic communication systems and be used to generate high-frequency and high-spectral purity RF signals [10].

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References

[1] N. A. Olsson and J. P. Van Der Ziel, "Characteristics of a semiconductor laser pumped Brillouin amplifier with electronically controlled bandwidth," *J. Lightwave Technol.*, vol. LT-5, pp. 147–153, Jan. 1987.
[2] C. L. Tang, "Saturation and spectral characteristics of the Stokes emission in the stimulated Brillouin process," *J. Appl. Phys.*, vol. 37, pp. 2945–2955, 1966.
[3] G. P. Agrawal, *Nonlinear Fiber Optics*. San Diego, CA: Academic, 1989, ch. 9.
[4] C. G. Atkins, D. Cotter, D. W. Smith, and R. Wyatt, "Application of Brillouin amplification in coherent optical transmission," *Electron. Lett.*, vol. 22, no. 10, pp. 556–558, 1986.
[5] J. A. Arnaud, "Enhancement of optical receiver sensitivities by amplification of the carrier," *IEEE J. Quantum Electron.*, vol. QE-4, p. 893, 1968.
[6] G. Gopalakrishnan, W. Burns, and C. Bulmer, "Microwave-optical mixing in $LiNbO_3$ modulators," *IEEE Trans. Microwave Theory Tech.*, vol. 41, no. 12, pp. 2383–2391, 1993.
[7] K. Yonenaga and N. Takachio, "A fiber chromatic dispersion compensation technique with an optical SSB transmission in optical homodyne detection systems," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 949–951, Aug. 1993.
[8] G. H. Smith, D. Novak, and Z. Ahmed, "Technique for optical SSB generation to overcome dispersion penalties in fiber-radio systems," *Electron. Lett.*, vol. 33, no. 1, pp. 74–75, 1997.
[9] X. S. Yao, Phase to amplitude modulation conversion using Brillouin selective sideband amplification," *IEEE Photon. Technol. Lett.*, to be published.
[10] X. S. Yao, "High quality microwave signal generation using Brillouin scattering in optical fibers," *Opt. Lett.*, vol. 22, no. 17, pp. 1329–1331, 1997.